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Experiences on solar heating and cooling in China

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Abstract

Solar energy is receiving much more attentions in building energy systems in recent years. Solar thermal utilization should be based on the integration of solar collectors into buildings. The facades of buildings can be important solar collectors, and therefore become multifunctional. In addition, solar collectors can be used to enhance the appearance of the façade when considering aesthetic compatibility. Currently, the feasible approach for integration of solar collectors into buildings is to install collectors on the south tilted roofs, south walls, balconies or awnings. Experiences on solar thermal utilization were mainly introduced in this paper, which included solar hot water systems with different design methods in residential buildings and solar-powered integrated energy systems in public buildings. Then the suggestions were given. In the cities of China, an ideal opportunity to carry out solar renovation with roof-integrated collectors is in combination with the rebuilding of apartment roofs from flat to be inclined. With regard to multi-storied residential buildings, central hot water supply system and central-individual hot water supply system are more appropriate in view of aesthetic compatibility of solar collectors with building roof and convenience of management. As for public buildings, it is highly recommended to design solar-powered integrated energy systems for the purpose of high solar fraction.

Keywords: Solar energy; Experience; Residential building; Public building

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Contents

1. Introduction

The fast developing China is now facing serious energy and environment challenges, such as high public health costs from severe air pollution arising mainly from coal combustion, energy security concerns over growing oil imports for transportation, limited domestic energy resources other than coal, projected demands for energy that will exceed domestic supply capabilities (even coal) within a few decades. In addition, China could become the world's largest emitter of greenhouse gases by 2020 [1]. All this issues bring China to consider sustainable development and scientific development, the unit GDP energy consumption is expected to get 20% down in 5 years.

The construction and operation of buildings greatly contributes to these energy and environmental loads. Currently, energy consumption in buildings mainly consists of domestic hot water, heating and air-conditioning systems, which accounts for approximately 25–30% of the total energy use in China. Although this proportion is lower than 40% of the developed countries, it is believed that such a proportion will be greatly increased with the rapid economic development of China [2,3].

The governments and engineers have begun to re-examine the whole approach to the design and control of building energy system. Consequently, it is of great importance in the building field to reconsider the building structure and exploit renewable energy systems, which can minimize the energy expenditure and improve thermal comfort.

Most of the building energy systems consumes electricity and gas that are high-grade energy. However, the required temperature of domestic hot water and heating (floor heating) is generally below 60 °C that belongs to low-grade thermal energy. Therefore, energy-saving systems including solar system and high-performance heat pump system are recommended to supply domestic hot water and heating for buildings especially for residential buildings. With regard to air-conditioning system, considering the problem of peak load of electricity in summer is due to electric power consumption for air conditioning, the idea of solar cooling is intriguing from demand side considerations: the chilling demand at least to a significant extent runs parallel to the availability of solar

radiation. Therefore, the interest in solar cooling by sorption systems has been prevalent for several decades [4].

In this paper, the concept of integration of solar collectors into buildings was introduced. Solar thermal utilization in buildings was reviewed. And then our experiences on solar thermal utilization were presented.

2. Solar thermal utilization in buildings

2.1. Integration of solar collectors into buildings

The facades of buildings can be important solar collectors. Multifunction facades, that provide daylight, electricity and heat in appropriate proportions, are therefore gaining attentions. When using the integrated approach, solar systems become part of the general building design. In fact, they also often become regular building elements. This is due to the fact that integrating solar systems with the building envelope is often a necessity if the systems are to be economically feasible. The solar collectors cannot be separate elements that are added after the building, they should at least be considered during the architectural design. They must rather replace other building elements, thereby serving dual functions and reducing total costs [5].

In Europe, there have been roof module collectors or solar roofs that have dimensions of about $20\,m^2$ and may include roof beams and roof insulation on request [6]. Palmero-Marrero et al. studied the modification of existing louver designs to integrate a solar collector in the shading device. A numerical model for the integrated solar collector was developed for different configurations and the collector efficiency was quantified for each configuration. The integration of collectors into the external louvers of buildings offers a means of reducing system cost as well as providing architects with more freedom to integrate the technology into their designs [7].

However, in most cases, it is not necessary to strive for total integration. The architects use the approach of aesthetic compatibility rather than of invisibility. Solar elements can be used to enhance the appearance of the façade, by providing variation, or contrast, or just by the fact that many solar elements in themselves are attractive—in shape, size, colour, and/or surface texture [5].

Tripanagnostopoulos et al. tested the different models outdoors, which were constructed with black, blue and red brown absorbers. Regarding the experimental and theoretical results, they estimated that solar collectors with colored absorbers are of interest for solar thermal applications, considering that they are more flexible than collectors with black absorbers for a variety of applications that require aesthetic compatibility of solar collectors with building architecture [8]. Another feasible integration of solar collectors into buildings is in the projects of building renovation. Voss [9] and Dalenbäck [10] reported that solar collectors may improve the building envelope, e.g. when a flat roof is rebuilt to an inclined "solar roof" or new space is created by adding a "solar attic" onto a flat-roofed building.

2.2. Present state of solar thermal utilization in china

Solar energy is abundant and clean. More than two-thirds of areas in China receive annual total radiation above $6000\,MJ/m^2$ with more than 2200 h of sunshine. It is

meaningful to substitute solar energy for conventional energy. Solar energy, therefore, has an important role to play in the building energy system.

Since 1980, solar water collectors have undergone a rapid development with an annual average growth of 30%. By the end of 2005, a total of over 60,000,000 m^2 solar water collectors were put into use nationwide. They are installed with the main purpose of preheating domestic hot water and/or to cover a fraction of the space heating demand. Currently, solar water heaters have accounted for about 10% market of the water heating devices. There is still a great market potential for solar water heaters in China. Solar water heating collectors have become an important mark of green buildings. In the 2008 Olympic projects of Beijing, as shown in Fig. 1, about 90% domestic hot water will be provided by solar collectors, which contributes greatly to the concept of green Olympics [11].

Solar-powered floor radiation heating system was testified to be an appropriate choice in solar thermal utilization because solar energy has the characteristic of low thermal flow density. Besides, it is difficult for the ordinary solar collectors on the market to attain high temperature. A typical instance of solar-powered floor radiation heating system is the newly built Lasa Railway Station in the famous Qingzang Railway project, as shown in Fig. 2. It is reported that indoor temperature of waiting room with solar-powered floor heating system can reach 20 °C in winter [12].

Fig. 1. Aeroview of Olympic Park of Beijing.

Fig. 2. Photo of Lasa Railway Station.

However, this application mainly for obtaining hot water through solar energy is not very consistent with the order of nature. In summer with high solar radiant intensity and high ambient air temperature, the demand for air-conditioning and refrigeration is in preference to hot water, this phenomenon is obvious especially in the south of China for example (now even in north China due to the serious climate changes in recent years). The prevalence of air conditioners has brought great pressure upon energy, electricity and environment. Consequently, solar-powered air-conditioning system would be a perfect scheme because it not only makes the best use of solar energy, but also converts low-grade energy (solar energy) into high-grade living demand for comfort. In addition, it is meaningful for the energy conservation and environment protection. Solar cooling has been shown to be technically feasible. It is particularly an attractive application for solar energy, because of the near coincidence of peak cooling loads with the available solar power. The research and development of solar cooling systems were mainly focused on the solar absorption air-conditioning systems. In the Ninth Five Year Research Project (duration 1995–2000), a large-scale solar absorption air-conditioning system driven by evacuated tubular solar collectors was built in Rushan, Shandong Province. The cooling capacity of this system is about 100 kW, with the average cooling COP of 0.57 in 6 h effective operation [13]. Another solar absorption air-conditioning system with the same cooling capacity driven by flat-plate solar collectors was constructed in Jiangmen, Guangdong Province. The experimental results showed that average cooling COP is 0.4 [14].

Another potential solar-powered air conditioning system is solar adsorption cooling system. It is a better choice to use adsorption cooling technology for minitype solar-powered air-conditioning systems [15]. Due to the intermittent cooling of adsorption system, adsorption refrigerator was used for solar ice making. For applications such as air conditioning, adsorption systems with two or more adsorption beds can be used to produce a cooling effect continuously. In 2004, Shanghai Jiao Tong University has broken through key technological difficulties, and invented a silica gel–water adsorption chiller that is suitable for solar-powered air-conditioning system. From then on, we have put it into practice in several projects, and accumulated plentiful experimental results of the system operating performance. Due to its use of low-temperature hot water (as low as 60 °C), such system can be operated continuously for about 8–9 h daily.

2.3. Design approach on integration of solar collectors into buildings

Currently, the familiar approach for integration of solar collectors into buildings is to install collectors on the south tilted roof. The heat storage water tanks can be placed in the attics or other special space. Through reasonable design, solar collectors can be directly mounted on the roofs by means of overhead (Fig. 3), imbedding (Fig. 4) and semi-imbedding (Fig. 5) installations. In addition, the integration of solar collectors with building roof can also be realized by specially designed steel structure, which has been experienced by us in the green building demonstration project of Shanghai. Compared with the former, this method has higher manufacturing cost; however, it is free of additional waterproof for the building roof. Moreover, it is capable of adding aesthetic gusto for building and incarnating modern building style.

Generally speaking, integration of solar collectors into building roof has the disadvantage of serious thermal loss led by long pipelines. Furthermore, the inspection

Fig. 3. Effect of solar collectors integrated into roof of building by overhead installation.

Fig. 4. Effect of solar collectors imbedding into roofs of buildings.

Fig. 5. Effect of solar collectors semi-imbedding into roofs of buildings [16].

on the roof is sometimes difficult and dangerous. Here, solar collectors can be considered to integrate with the south elevation, and form consecutive façade with rhythmical image. The feasible methods include integrations of solar collectors with balconies (Fig. 6), walls (Fig. 7) and awnings (Fig. 8).

Fig. 6. Effect of solar collectors integrated into balcony of building [17].

Fig. 7. Effect of solar collectors integrated into wall of building.

Fig. 8. Effect of solar collectors integrated into awning of building [18].

The integration of solar collectors with balconies and walls is convenient for checking. Besides, it has the advantages of shorter pipelines and less civil work. However, proper solar collector type must be chosen to adapt building façade. In addition, building design

must be adjusted to prevent sun shading by building itself. Another adjustment such as space function should also be carried through for the purpose of effective utilization of solar energy system. The integration of solar collectors with awnings that can generally be applied in low storied buildings is realized by placing solar collectors on the bracket of awning over the window.

Solar collectors may also form multifunctional building components, and therefore act as balcony sideboard, exterior facing of wall or awning except supplying hot water. Such designs effectively make use of building space.

As an industrialized technical product, solar collectors can be used to create building shape with personality by integration with building compactly. Fig. 9 shows effect of solar collectors acting as roof decoration [19]. Solar collectors surrounded by arc iron sculpt perk up in the middle. The flexible lines of iron sculpt and the square-built solar collecting plane combine to form one integrated mass. Fig. 10 shows effect of solar collectors acting as southing facade decoration of a flat roofing building. It is seen that the façade expresses the effect of tilted roofing because of regular installation of solar collectors behind the eaves.

Fig. 9. Effect of solar collectors acting as roof decoration [19].

Fig. 10. Effect of solar collectors acting as southing facade decoration.

3. Our experiences

3.1. Solar thermal utilization in residential buildings

Considering the integrated approach, we designed solar hot-water systems in the solar lab of Shanghai Jiao Tong University. For the purpose of demonstration for the familiar roofing style of residential buildings in Shanghai, both evacuated tubular solar collectors and flat plate solar collectors were integrated into cement tile roofing, as shown in Fig. 11(a). However, Fig. 11(b) shows integration of solar collectors with asphalt shingle roofing which is a kind of recommendatory roof style in the projects of the rebuilding of apartment roofs from flat to inclined.

In Shanghai Research Institute of Building Science, a three-storied green building was built for the demonstrations of flats, where the first floor is for ordinary single-storied flat and the upper two floors are for duplex flat. The solar collectors were installed on the sideboards of balconies. According to the dimension of balconies, we customized 0.75-m-high U-type evacuated tubular solar collectors with CPC, and placed 5.6 m^2 solar collectors for the first floor, 2.7 and 4.2 m^2 for the second floor and third floor, respectively. Fig. 12 shows the effect of integration of solar collectors and the flat. Here, solar collectors act as not only the heat source of hot-water system, but also the decoration of balconies. This demonstration project serves as a good example of both building integration and a sensible combination of functions. Moreover, it provides a feasible design method for multi-storied buildings and high-rise buildings especially for residential buildings that are widespread in large cities like Shanghai.

The solar hot-water system is mainly composed of a solar collector array, a pump, a constant pressure tank and a heat-storage water tank of 0.3 m^3 in volume. They are connected through copper pipes and valves to form a closed circulating system with a setting pressure of 0.4 MPa. In this system, the operation of the pump is controlled by the temperature difference between solar collectors and the heat storage water tank. Consequently, the collected solar heat is extracted whenever it is available. The domestic hot water is heated by the heat exchanger inside the heat storage water tank.

In order to realize all weather hot-water supply, an electric heater was encased in the heat storage water tank. Under weather condition of Shanghai, the annual solar collecting efficiency of this solar water heating system is about 36–40%. In addition, the solar

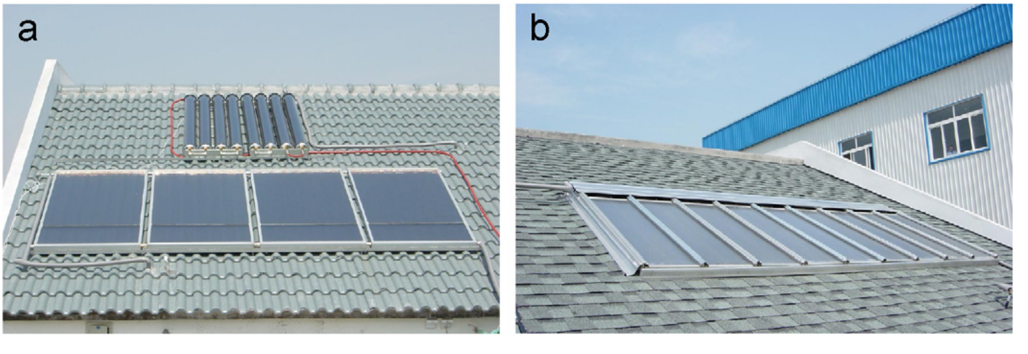

Fig. 11. Demonstration of solar collectors integrated with residential roofing. (a) Integration of solar collectors with cement tile roofing. (b) Integration of solar collectors with asphalt shingle roofing.

Fig. 12. Effect of integration of solar collectors and flat.

Fig. 13. Effect of integration of solar collectors and villa.

fraction is 70% annually. We have strongly recommended air source heat pump water heater as an effective auxiliary heating system, the electric consumption of such heat pump water heater is only 25% of that of electric heater.

In the demonstration of a villa, because the whole roof is occupied by technologies of solar photovoltaic and greening, we customized 1-m-high U-type evacuated tubular solar collectors with CPC in terms of the dimension of awning, on which we installed 4.6 m^2 solar collectors as shown in Fig. 13. Such design provides another example of how a solar element could be used in the original design in a logical manner, especially for those buildings without enough roof area. The hot-water system in the villa is similar with that of flat except that an air source heat pump water heater is installed in parallel with solar collectors, acting as auxiliary heat source. When solar energy is insufficient, the air source water heater is turned on. Such design decreases annual operating cost by about 75% compared with solar water systems with electric heater as auxiliary heat source.

In the Fudi Real estate Company, there are two demonstration villas. One of which was constructed with a solar-powered integrated energy system involving floor heating and domestic hot water supply. All-glass evacuated solar collectors of area 10 m^2 were placed on the flat roof through supporting frame, as shown in Fig. 14. A mini-type gas boiler was

Fig. 14. Photo of villa of Fudi real estate company.

Fig. 15. Photo of air source heat pump water heater.

used to act as auxiliary heat source. By means of automatic control system, the solar-powered integrated energy system is capable of running either by solar energy alone or by the combination of solar energy and gas. The system has been debugged successfully, and put into use currently.

The hot-water system in another villa of Fudi Real estate Company is powered by air source heat pump water heater invented by us. It is composed of an indoor heat storage water tank and an outdoor evaporator, as shown in Fig. 15. Such water heater is free of complex integrated design. Our experimental tests have shown that the mean annual COP attains 4.0. Moreover, it is testified to be quite reasonable and economic for the applications in Shanghai according to the all-rear experimental results.

3.2. Solar thermal utilization in public buildings

An integrated solar energy system including heating, air conditioning, natural ventilation and hot water supply was designed for the green office building of Shanghai Research Institute of Building Science. We installed 150 m^2 solar collectors on the roof of the green office building acting as the power to drive adsorption chillers and the heat source for the floor heating and natural ventilation, wherein U-type evacuated tubular solar collectors with CPC of area 90 m^2 were placed on the west side (SCW), and the other 60 m^2 heat pipe evacuated tubular solar collectors on the east side (SCE). Such two type

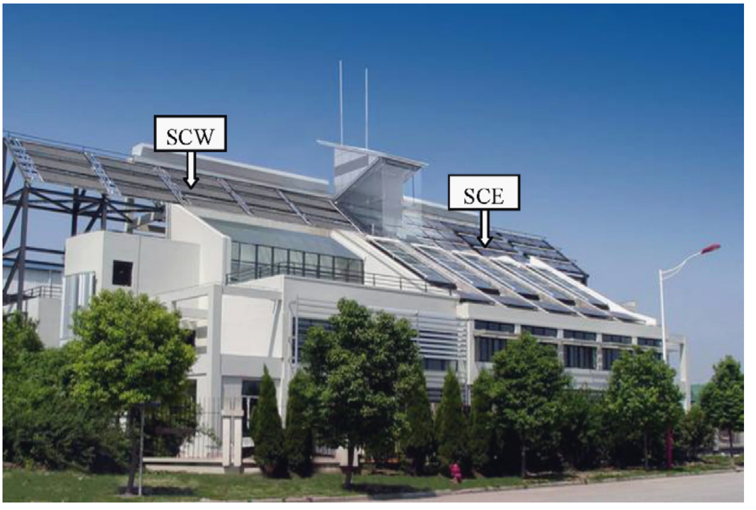

Fig. 16. The external appearance of the green building integrated with solar collectors.

solar collectors are typical in China; this arrangement is used for the purposes of comparisons. For the purpose of efficient utilization of solar energy, the architects designed a steel structure roof, facing due south and tilted at an angle of 40° to the ground surface (such angle is mainly considered for the efficient use of solar energy in summer for air conditioning in Shanghai), on which the solar collectors were mounted and integrated with the building perfectly. Fig. 16 shows the appearance of the green building integrated with solar collectors. All solar collectors of both sides were divided into three parallel rows. The collector units in each row were connected in a series arrangement for the purpose of obtaining hot water with relatively high temperature, which plays an important part in improving performance of the solar energy system. Such an arrangement of solar collectors not only guarantees high system performance but also enhances the architectural expression of the building. Besides, it provides a feasible idea for integration of solar collectors and civil buildings especially for public buildings.

The integrated solar energy system can be switched to different operating modes according to different seasons:

(1) In summer, the cooling load of air-conditioning area under design condition is 60 kW, in which 15 kW is sensible heat cooling load met by solar-adsorption air-conditioning system, which is discussed in this paper. The other 45 kW is latent heat cooling load taken on by a liquid-desiccant system, which is constructed by Shanghai Research Institute of Building Science. Thereby, the hybrid air-conditioning system deals with cooling and humidity loads independently, and the fan coils inside air-conditioning rooms realize dry operating mode. The system of solar adsorption cooling had been operated independently to supply cooling to 460 m^2 building area, which provided acceptable cooling comfort. In a typical sunshine day in July, the maximum cooling power was 21 kW, the averaged cooling power was 15.31 kW in a day from 9:00–17:00. The electric COP reached over 10.

(2) In winter, solar-powered floor radiation heating system is used to satisfy heating load of the green building. The experience of 460 m^2 building area heating is acceptable.
(3) In transitional seasons, solar hot water is pumped into finned tube heat exchangers to induce stack pressure, which is capable of improving natural ventilation.
(4) The system can be used to supply hot water as long as a heat exchanger is installed in parallel with what mentioned above.

From September 2004 to August 2005, the solar-powered integrated energy system was continuously in operation under different modes according to different seasons. Based on all-the-year-round experimental data, it is concluded that under the climate condition of Shanghai, 150 m^2 evacuated tube solar collector arrays can be used to satisfy heating and air conditioning for covered area of 460 m^2. Under typical working condition in winter, the average floor temperature and indoor air temperature is about 23.71° and 17.10°, respectively, which satisfies indoor thermal environment. Under typical working condition in summer, the average refrigerating output of solar powered air-conditioning system is 15.31 kW during operation of 8 h; moreover, the maximum attains 21 kW. In addition, under typical working condition in transition seasons, the system is capable of inducing air change rate of 3 ACH and supplying hot water for the office building.

Also can be obtained is that the solar fraction for the system in winter is 56%, correspondingly, 75% in summer and 68% in transition seasons. Then the mean annual utilization ratio of the system nearly reaches 70% through weighted average calculation of solar fractions in different seasons and the corresponding days.

A similar solar integrated energy system has been constructed for the workers' eatery of Jiangsu Huayang Solar Company. We used support frame to install all-glass evacuated solar collectors on the flat roof, as shown in Fig. 17. The system is capable of floor heating in winter, air conditioning in summer and all-year hot water supplying.

Recently, we have established another solar-powered integrated energy system in the new solar lab of Shanghai Jiao Tong University (Fig. 18). In this project, we have installed 100 m^2 U-type evacuated tubular solar collectors with CPC on the roof, facing due south and tilted at an angle of 30° to the ground surface. The collected solar heat is stored in the water tank through indirect heat exchange between the water tank and the pressurized collector loop. A newly developed adsorption chiller with the rated cooling capacity of

Fig. 17. The external appearance of the workers' eatery integrated with solar collectors.

Fig. 18. The new solar lab of Shanghai Jiao Tong University.

Fig. 19. Photo of adsorption chiller.

10 kW is chosen to meet the cooling load of the lab (Fig. 19). The floor heating coil pipes made of polyethylene are laid in the covered area of 170 m^2 (Fig. 20). Besides, three shower nozzles are prepared for students. The performance of this system will be studied in detail after the installation. Some new considerations of ceil cooling has been used for testing, the solar heating system has been also considered as a heat source to power desiccant cooling system. Detailed experimental results are expected to be shown in next year.

4. Lessons and suggestions

4.1. Residential buildings

Solar heating could be an important contributor in the residential sector for hot-water supply and space heating. For new buildings, solar collectors can be mounted on walls, balconies and awnings besides roofs, on condition that solar systems become part of the general building design. Solar elements therefore could be used in the original design in a logical manner for the purpose of supplying hot water as well as improving building faç ade. Such integrated approach is especially feasible for multi-storied residential buildings.

Fig. 20. Photo of floor heating coil pipes.

In cities of China, an ideal opportunity to carry out solar renovation with roof-integrated collectors is in combination with the rebuilding of apartment roofs from flat to be inclined. Solar renovation concepts involving improvements that change the appearance of the façade, however, may be restricted if maintaining the architecture of the original building is an important consideration. The approach of solar collectors integrated into roof has an advantage in this respect, since the new façade, on the whole, may be given the same appearance as the original one.

With regard to multi-storied residential buildings, central hot-water supply system and central-individual hot-water supply system are more appropriate in view of aesthetic compatibility of solar collectors with building roof and convenience of management. Solar collectors can be flat plate or evacuated tube solar collectors and integrated into building compactly. Fig. 21 shows flow diagram of central hot-water supply system, which arranges a centralized heat storage water tank in the water tank space or attic to collect solar heat. The hot water is supplied to users from the heat storage water tank by the hot water pump. Fig. 22 shows flow diagram of central-individual hot water supply system. The solar collectors in combination with heat storage water tanks that are placed individually forms a pressurized collector loop. Hot water is supplied by the pressure of tap water. The aforementioned hot-water supply systems require unitized management. Another type that is individual hot-water supply system as shown in Fig. 23 is more suitable for villas or houses. However, it can be applied in multi-storied residential buildings as long as solar collectors are integrated with balconies or walls of buildings.

Based on our experiences in Shanghai, the annual operating cost between solar water heater, diesel oil boiler, gas boiler and electric water heater is compared as shown in Fig. 24. It is deduced that, under otherwise identical conditions (daily hot water consumption of 150 kg with water supply temperature of 60 °C), solar water heater is the most economical domestic hot water system. Compared with electric water heater, the annual operating cost of solar water heater decreases by about 70%.

But the recent development of air source heat pump water heater have shown another attractive perspectives, such system consumes electricity, but takes three times more energy from the ambient, such system can supply hot water all the time, and can be used as a thermal storage hot water system to use the low price valley electricity. Due to its no restriction of installation (north side, even in high rise buildings), air source heat pump

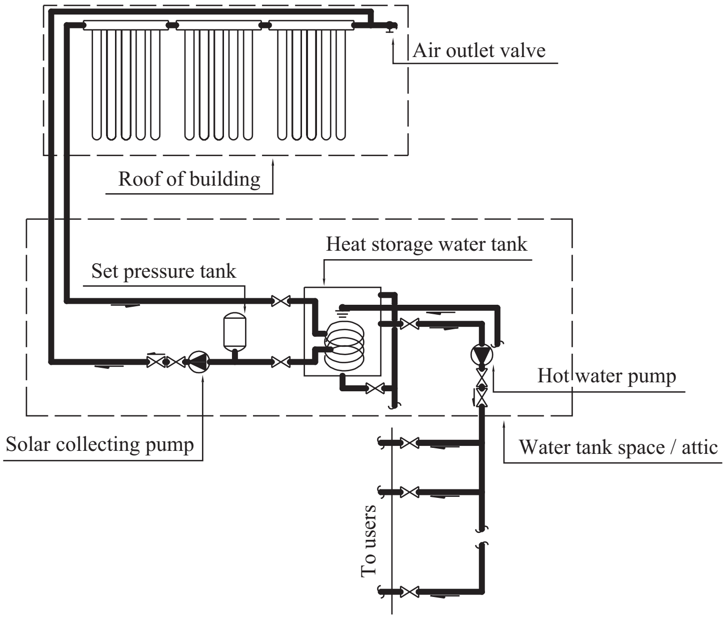

Fig. 21. Flow diagram of central hot water supply system.

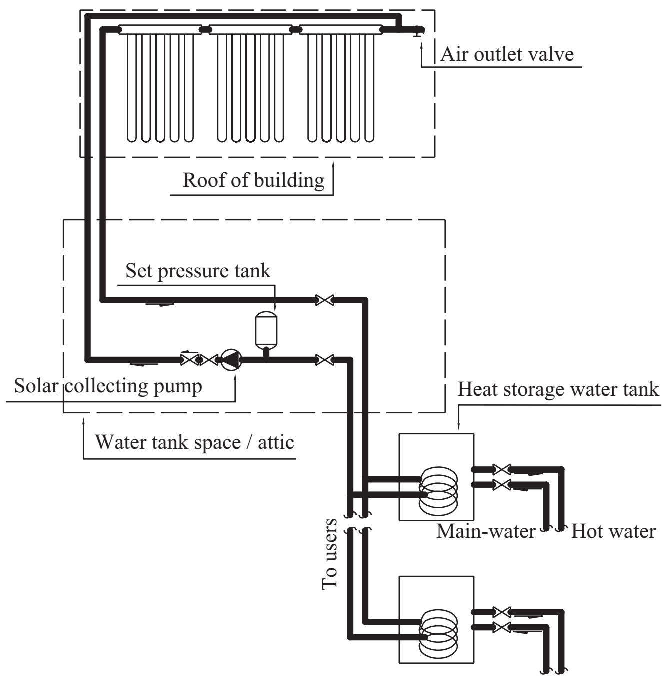

Fig. 22. Flow diagram of central-individual hot water supply system.

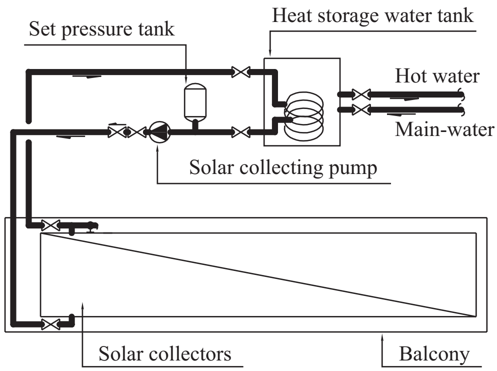

Fig. 23. Flow diagram of individual hot water supply system.

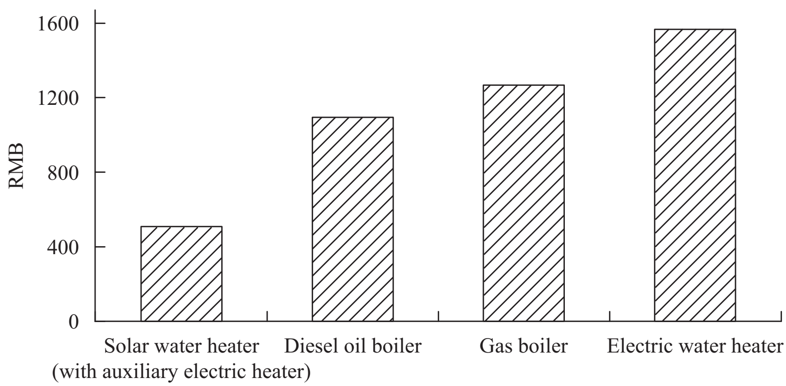

Fig. 24. Comparison of annual operating cost between solar water heater, diesel oil boiler, gas boiler and electric water heater.

water heater system are quite attractive, specially in the areas with winter temperature above $-10\,^{\circ}\mathrm{C}$ and the area without enough sunshine times annually, examples are near Shanghai Yangzi River area and the south part of China. In this case, air source heat pump water heater can be a competitor of solar water heating system.

4.2. Public buildings

As for public buildings, it is highly recommended to design solar-powered integrated energy systems. Owing to the fact that there are always enough roof area to install solar collectors, solar-powered integrated energy systems are capable of supplying cooling and heating, even enhancing natural ventilation besides hot water supply. Such designs have the advantages of high utilization ratio, strong adaptability to seasons, and thus high solar fraction, which makes the solar-powered integrated energy systems more economical.

The pay back period is about 2 years if hot water is consumed directly for bath or shower for such buildings. The pay back period could be 5–8 years if the hot water is used only for space heating and cooling for the building.

4.3. Prospects

Global warming, ozone depletion and energy shortage have intrigued widespread research of renewable energy. Being abundant and clean, solar energy is receiving much attention in building energy system. The utilization of solar energy is a wise option for human beings to preserve our planet and sustain rapidly economic development. With the implement of "Renewable Energy Law of China" since January 1, 2006, enough emphasis was put by the governments of all provinces. Taking Shanghai for example, the government has issued "Program of Exploiting and Using Solar Energy", which calls for notable effect of solar thermal utilization in 3–5 years. Accordingly, by the year 2007, there will be 100,000 m^2 (solar collecting area) solar hot water systems integrated with buildings in Shanghai. In 2010, the equivalent solar collecting area will be extended to 2,500,000 m^2, in which both solar water heating and air source heat pump water heating systems will be used. It is reasonable to expect that the solar thermal utilization will play greater role in building energy systems in the coming years.

Acknowledgments

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